The Practical Guide to Lake Management in Massachusetts

A Companion to the Final Generic Environmental Impact Report on Eutrophication and Aquatic Plant Management in Massachusetts

Commonwealth of Massachusetts
Executive Office of Environmental Affairs

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Prepared for the

Department of Environmental Protection
and
Department of Conservation and Recreation

Executive Office of Environmental Affairs,
Commonwealth of Massachusetts

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INTRODUCTION: ABOUT THIS MANUAL

This manual has been prepared as a companion guide to the Final Generic Environmental Impact Report (GEIR) on Eutrophication and Aquatic Plant Management in Massachusetts (Mattson et al. 2004). The GEIR is a larger document with more information, intended to satisfy the requirements for such a document under the Massachusetts Environmental Policy Act. This companion guide was developed to provide key information in a more concise and user-friendly format for Conservation Commissions, lake groups, and interested citizens. As this guide was developed from the GEIR, the efforts of all those involved in the preparation of the GEIR are acknowledged, especially Drs. Mark Mattson and Paul Godfrey, the primary authors of the original version of the GEIR, from which much of the information in this manual is taken.

The focus of this guide is on key aspects of each potential lake and watershed management technique that might be considered for the control of eutrophication and aquatic plants. It is intended to provide the reader with a general overview and enough information to evaluate whether or not a given technique is appropriate to the situation. It also indicates issues for each technique that must be considered in a more thorough feasibility assessment. For those involved with managing a lake, this manual provides information essential to understanding options and narrowing the choices, but is not always a substitute for competent advice from lake management experts. For Conservation Commissions, this guide highlights the salient issues that must be addressed if a management technique is to be applied properly under the Wetlands Protection Act and associated statutes. However, it cannot anticipate and address all possible situations that may arise or every factor that may go into a decision.

Lake and watershed management is a complex process that is interdisciplinary by nature and involves so many facets that it is difficult to know where to start in many cases. Compromises are almost always made between study and action, protection and conservation, restoration and maintenance, and expense and expedience. With limited time, funding and information, such compromises may indeed be necessary, although the regulatory framework within which management actions are permitted has minimum standards that set limits on management without appropriate justification. Iterative steps in the management of watersheds and lakes is often encouraged; small steps that move in the perceived correct direction cost less and have less potential to damage non-target organisms or features. However, some techniques are not effective unless applied at a larger scale, and ultimately the cost of management may be quite high. This guide cannot provide the solution to all potential problems or the answer to all possible questions, but it does provide a substantial amount of information intended to start interested groups in the right direction.

The organization of this manual is simple. Following this introduction is a section on lake and watershed features and processes, which is considered essential information for understanding management techniques and associated issues. Then there is a brief section on developing a lake and watershed management plan, distilled from the more lengthy discussion in the GEIR. The remainder of the manual is a compendium of management techniques aimed at controlling the input of nutrients or the accumulation of vascular plant and algal biomass. For each technique there are concise sections on how it works, what benefits it can provide, significant shortcomings or potentially undesirable impacts, factors that favor its use, information necessary to proper application, implementation guidance, permits that may be needed, and approximate costs. The information in this manual is abridged from the GEIR, and readers are encouraged to review relevant sections of the GEIR to gain additional insight on techniques of interest. Readers may also want to consult the references provided in this guide and in the more extensive ones in the GEIR, and should consider consulting relevant websites for updates and additional information. Two especially relevant websites are those of DEP's Watershed Management Program (www.state.ma.us/dep/brp/wm/wmpubs.htm) and DAR's Pesticides Program (www.state.ma.us/dfa/pesticides/water/aquatic/herbicides.htm).

ESSENTIAL BACKGROUND INFORMATION

The Origin and Nature of Lakes

The lakes in Massachusetts were created in two principal ways: by glacial activity approximately 12,000 years ago or by damming streams or small lake outlets, most of latter occurring during the early industrial age of the country for water power. In many respects, lakes are like people. They are born, grow older and die, with many possible conditions along the way. Through natural processes, lakes will become shallower and more eutrophic (nutrient-rich) and eventually fill in with sediment until they become wet meadows. The aging process is not identical for all lakes, however. Some lakes age quickly, others very slowly, and not all start out in the same condition. Many lakes that were formed by the glaciers no longer exist while others have changed little in 12,000 years. Yet lake aging is reversible. The rate of aging is determined by many factors including the depth of the lake, the nutrient richness of the surrounding watershed, the size of the watershed relative to the size of the lake, erosion rates, and human induced inputs of nutrients and other contaminants. Lakes are therefore highly variable in specific features, and goals for the management of each may vary as well.

Existing lakes can be subdivided into categories depending on their position along a continuum of fertility. Nutrient-poor lakes are termed oligotrophic, nutrient-rich lakes are eutrophic, and those in between are mesotrophic. Variations on this system are possible, and any system to boil the complexity of a lake into a single word will not be completely adequate to describe lakes. Lakes in one part of the Commonwealth may share many characteristics (depth, hydrology, fertility of surrounding soils) that cause them to be generally similar. Massachusetts can be divided into regions based on typical phosphorus levels in lakes (Figure 1).

Lakes that are created by damming streams may at first be eutrophic as nutrients in the previous stream's floodplain are released into the water column. Over a period of decades, the initial productivity tends to change until the impoundment takes on conditions governed more by the entire watershed, with depth and detention time as critical determinants of response to watershed inputs. Impoundments may never completely escape the legacy of their creation. They are commonly shallow and the pre-existing nutrient-rich bottom sediments may provide nutrients for abundant aquatic plant growth early in the life of the lake.

Human activity can unduly accelerate the process of lake aging or, in the case of introduced species or pollutants, force an unnatural response. Unnatural responses include the elimination of aquatic species as a result of acid deposition, algal blooms resulting from excessive nutrient enrichment, and the development of a dense monoculture of a non-native aquatic plant. However, it would be unrealistic to assume that managing cultural impacts on lakes can convert them all into infertile basins of clear water. Understanding the causes of individual lake characteristics (i.e., understanding the lake ecosystem) is a fundamental part of determining appropriate management strategies.

An ecosystem is a system of interrelated organisms and their physical-chemical environment. We need an operational unit that can be reasonably studied and will help explain all or most of the characteristics of the lake. The most useful definition of the lake ecosystem is the lake and its watershed because the watershed defines the terrestrial sources of the lake's water (Figure 2). Most impacts on lakes can be related to characteristics of the watershed, although acid rain, mercury deposition and drought have demonstrated that not everything important to lakes occurs within the watershed. A lake is a web of interactions between hundreds of biological species, chemical compounds, hydrological processes and human actions, all in constant change. A tug on any part of the web ripples throughout the rest of the ecosystem. Ecology is the scientific study of these relationships and limnology is the study of freshwater ecology. Lake management involves the application of ecological principles and data to establish and maintain desirable conditions.

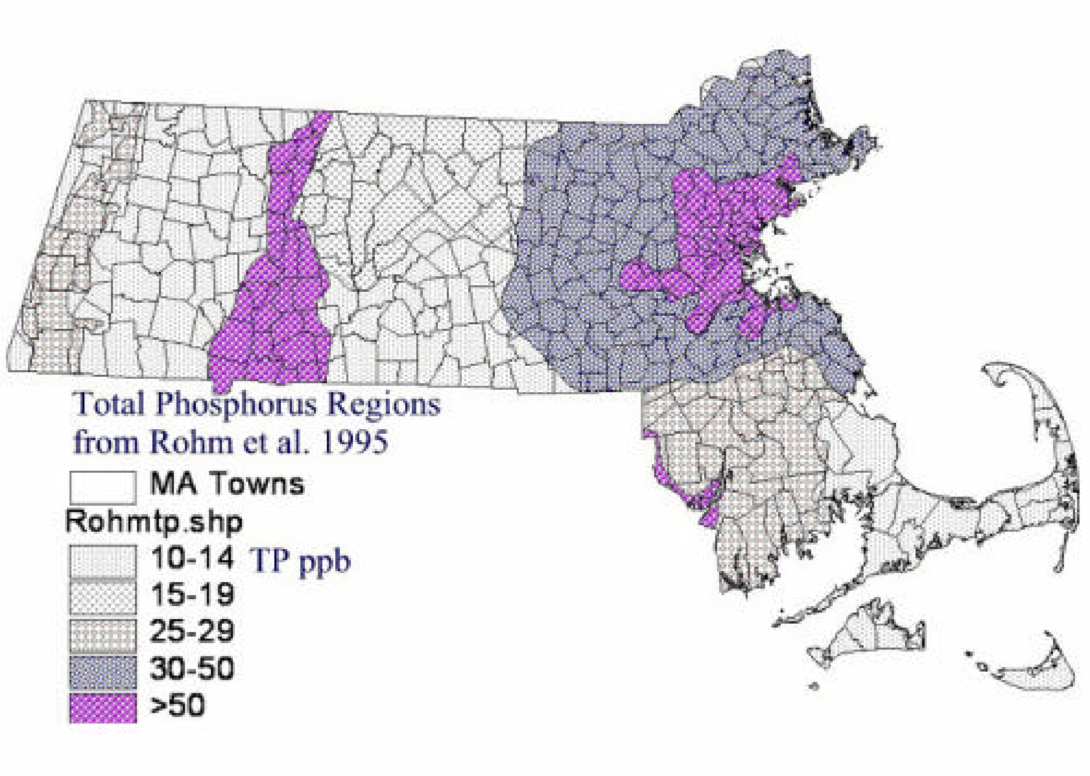

Figure 1. Regions of Massachusetts Based on Phosphorus Levels in Lakes (after Rohm et al. 1995)

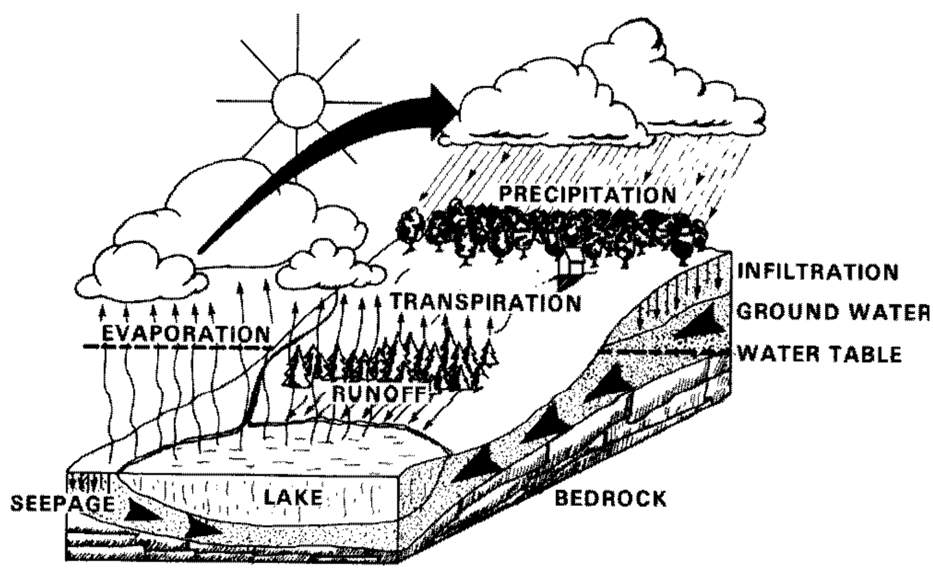

Figure 2. The Hydrologic Cycle (Olem and Flock, 1990)

Key Features of Lakes

Water

Water is very abundant both on earth and in all living organisms. Water has properties that make life in lakes possible, particularly lakes in the northern parts of the world. Unlike most other compounds, water does not become increasingly denser as it becomes colder. Instead, water increases in density as it is cooled until it reaches 4^{o}C (39^{o}F). Upon further cooling to 0^{o}C (32^{o}F), it becomes lighter and floats on the surface until it has cooled sufficiently to freeze. If this were not true, lakes would freeze solid in our winters. Water also has a high specific heat and high latent heat of fusion; thus they are slow to thaw in spring and slow to cool in winter, thereby providing an extremely stable thermal environment for aquatic life. Water also vaporizes at temperatures common to our climate, producing water vapor and continuing the hydrological cycle of precipitation, runoff and infiltration, evaporation and transpiration. Water is one of the best solvents available and many compounds dissolve in it. These properties help to explain much of what we observe in lakes.

Hydraulic Residence

The average time required to completely renew a lake's water volume (lake volume divided by outflow rate) is called the hydraulic residence time. Hydraulic residence time is a function of the volume of water entering or leaving the lake relative to the volume of the lake (i.e., the water budget). The larger the lake volume and the smaller the inputs or outputs, the longer will be the residence time. Lake residence time may vary from a few hours or days to many years. Lake Superior, for example, has a residence time of 184 years. However, Massachusetts lakes typically have residence times of days to months. Our largest lake, Quabbin Reservoir, has a residence time of approximately three years. Mill Pond in West Newbury, MA with an area of 16 acres and mean depth of 4.1 feet has a residence time of 14 days, while Lake Massasoit (aka Watershops Pond, an impoundment of the Mill River) in Springfield has an average residence time of about a week. The flushing rate of a lake will determine how it responds to many inputs.

Mixing

The thermal structure of lakes also helps determine productivity and nutrient cycling. Lake thermal structure is determined by several factors. Lakes receive the vast majority of their heat at the surface from solar heating. Since warmer water floats, the water column must have an energy input to mix that heat deeper and in most lakes wind provides that energy. A lake that is completely protected from the wind will have a very warm but shallow layer at the surface with cold water below. A lake exposed to strong winds will have a cooler but thicker upper layer overlying the colder water. For many shallow Massachusetts lakes, the mixed layer may extend to the lake bottom. Deeper lakes may form a three-layered structure that throughout the summer consists of an upper warm layer (the epilimnion), a middle transition layer (the metalimnion, within which the point of greatest vertical change is called the thermocline), and a colder bottom layer (the hypolimnion).

A lake's thermal structure is not constant throughout the year. Beginning at ice out in early spring, all the lake's water, top to bottom, is close to the same temperature; the density difference is slight and water is easily mixed by spring winds. With warmer days, the difference between the surface and bottom waters increases until stratification occurs if lake depth is sufficient (Figure 3). Eventually, solar heating declines and the upper layer begins to cool and sink. Eventually in the fall, the lake has a similar temperature top to bottom. In winter, ice forms at the surface and a new, inverse stratification (cold over cool water) is created and persists until spring. The degree of stratification is important to the cycling of nutrients, variability in oxygen in deeper waters, movement of incoming water through the lake, and types of aquatic organisms that live in the lake (Figure 3).

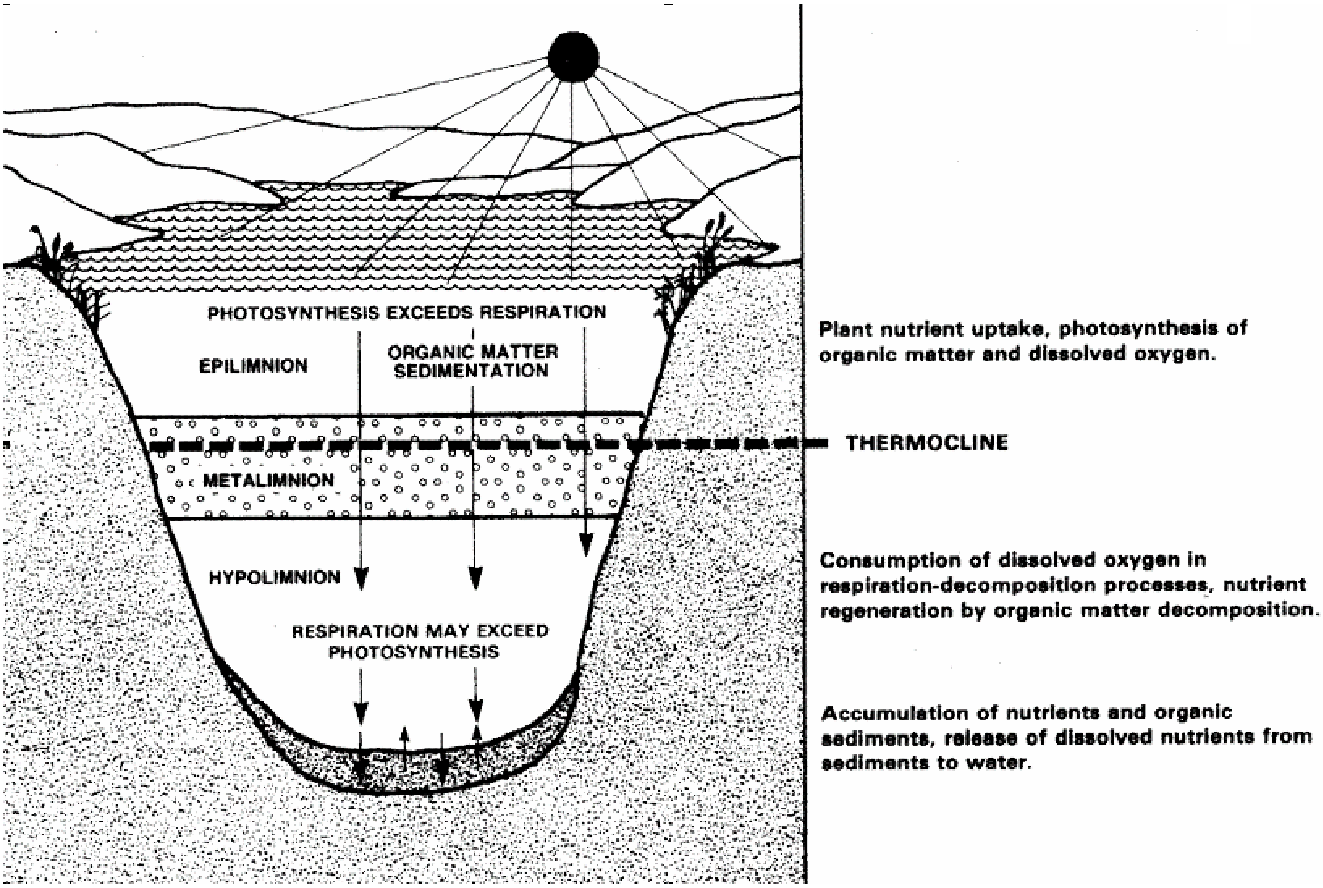

Figure 3. Influences of Photosynthesis and Respiration/Decomposition Processes on Oxygen and Nutrients in a Stratified Lake (after Olem and Flock, 1990)

Nutrients

Lakes may suffer from many impacts of human cultural development. Of primary concern for this review are nutrients. All plants need an appropriate balance of the essential major nutrients, particularly phosphorus, nitrogen, and carbon. They also need light. Assuming that light is readily available, plants take up nutrients in the proportion that their cells require. The nutrient that is in shortest supply relative to the plant's needs will limit the growth of the plants. This is called the limiting nutrient concept. The ratios of plant needs to the concentration of nutrients in water suggest that phosphorus is the scarcest nutrient relative to plant demand for most freshwater systems. Some freshwater and most estuarine systems have nitrogen as the limiting nutrient, and trace elements can sometimes be limiting, but phosphorus is the logical target of management to control algae in lakes. Phosphorus is easier to control than many other nutrients, particularly carbon and nitrogen. The latter two have gaseous phases, so the atmosphere becomes a major source where both are quite abundant.

Lake managers typically compartmentalize all forms of phosphorus into three categories: dissolved, particulate and their sum, total phosphorus. Dissolved phosphorus is readily available for uptake by plants and, consequently, is usually found only in low concentrations during the growing season. At that time, most of the phosphorus will either be adsorbed to particles such as fine soil or clay or in living or dead plant or animal cells. However, the death and decay of an organism will begin the process of releasing the phosphorus in dissolved form where it can almost instantly be taken up by other organisms.

A map of typical total phosphorus levels for Massachusetts lakes provides a general expectation of phosphorus concentration for any lake under study (Figure 1). While this does not provide a quantitative breakdown of nutrient sources that can help pinpoint likely areas for nutrient control, it can provide a sense of the typical conditions for the region and suggest reasonable goals for nutrient management. A lake with much higher phosphorus levels than typical for that region may be a strong candidate for successful improvement by reducing cultural sources of phosphorus. Keeping phosphorus concentrations below the expected level for the corresponding area may require frequent management action.

Development of a nutrient budget (loading analysis) provides insight into the causes of lake eutrophication. Nutrient budgets depend on the determination of the amounts of a nutrient that are provided by sources such as natural surface runoff, non-point source pollution, leaking septic systems, atmospheric deposition, groundwater and wildlife. Nutrient budgets also determine the quantity of nutrients lost to the lake system by outflow and by deposition to the sediments. Quantifying nutrient loading requires assessment of the water budget and determination of the concentration of the nutrient in each source of water. Thus the quantity of nutrient provided by a tributary is the concentration times the volume of water per unit time (the flow). This is called the "load" for the nutrient and source being quantified. Just like a bank account, the input loads (deposits) minus the output mass (withdrawals) should equal the total change in the mass of nutrient in the lake. Knowing the relative inputs and costs of reducing them aids the development of a workable lake management strategy for controlling water quality and therefore preventing algal blooms. Nutrient budgets are less useful in the control of rooted aquatic plants.

Internal loading refers to nutrients recycled from the sediments. Internal loading may be a large source of phosphorus to the lake in certain circumstances. When lake sediments become anoxic as they would in a stratified eutrophic lake, phosphorus that is normally adsorbed to iron oxides under oxygenated conditions is released in dissolved form. This hypolimnetic phosphorus may be returned to upper water layers during turnover or even during stratification under unusual circumstances. Also, resuspended sediment (caused by wind or motorized watercraft) may release phosphorus back into the water column. Additional phosphorus may be "pumped" from shallow water sediments by aquatic macrophytes with roots in the sediment, particularly when the plants die at the end of the growing season. As might be expected, such internal phosphorus loading is often hard to estimate. The timing of this internal loading may make it more important than its magnitude suggests; internal cycling of nutrients may not be important in a yearly budget, but may be very important during the summer stratification period, which is also the growing season.

Nutrient budgets are commonly determined in two primary ways: by direct measurement or by estimation from various empirical relationships determined in past studies. Accurate determination of a nutrient budget by direct measurement is monitoring-intensive, requiring nearly constant measurement of water flow and frequent measurement of nutrient concentration in all or most incoming and outgoing components. One rainstorm may provide a large percentage of the nutrient input; if unmeasured or not measured with sufficient frequency at sufficient sites, the budget will be grossly in error. Groundwater samples may be difficult and/or expensive to collect. Flow rates are hard to determine precisely without expensive automated equipment, especially during storm events.

It is rarely possible to achieve or afford this level of monitoring. Consequently, nutrient budgets are often determined by loading estimates based on land uses and by models established from large databases. Detailed research on many watersheds has provided important loading factors or export coefficients to be expected from various types of land use, numbers of residents, sediment storage and other more easily measured factors. The quality of the nutrient budget will depend on the similarity between the study watershed and the calibrated watersheds in the literature. No method is likely to produce a very accurate estimate of the nutrient budget if monitoring frequency is low or if the watersheds are only moderately comparable. However, the credibility of the estimate can be substantially increased if multiple methods are used and produce roughly comparable results. Agreement among multiple models, especially when calibrated for the study watershed with some real data specific to that system, can increase confidence in budget estimates. Key parts of a nutrient budget are shown in Figure 4. Generation of nutrient budgets is essential to many algal control efforts, but is less applicable to rooted plant control.

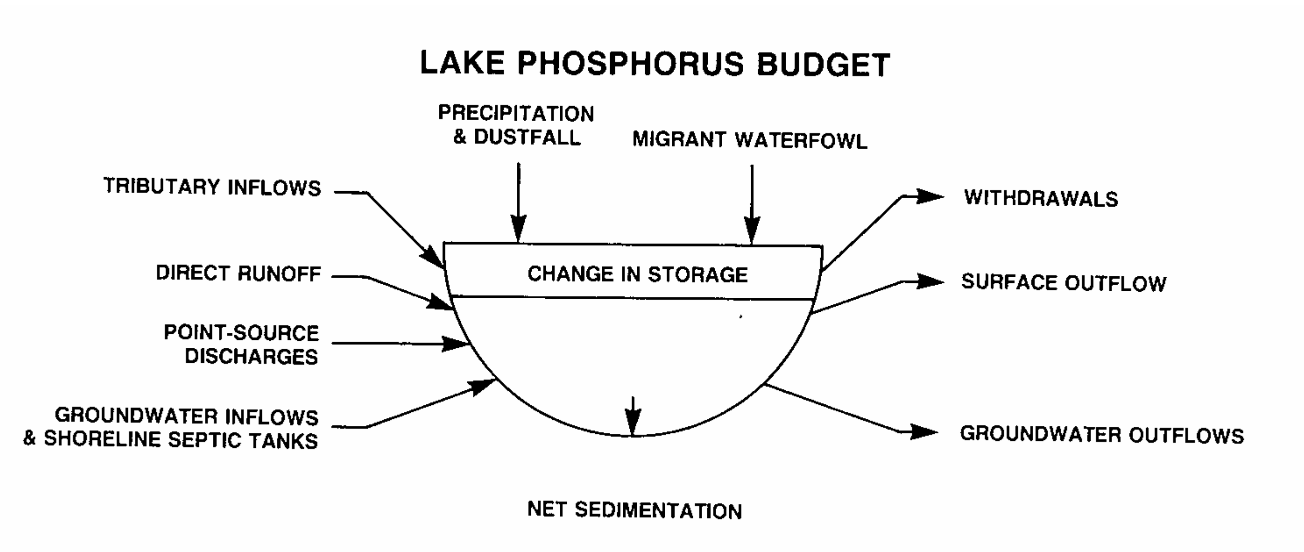

Figure 4. Elements of a Phosphorus Budget (after Olem and Flock, 1990)

Particulates

Particulates may be either inorganic or organic, but lake managers typically define them as any object larger than 0.45 thousandths of a millimeter (0.45 micrometers). Larger particles will not stay suspended in water for long, but smaller particles may settle very slowly or not at all. Colloids are fine particles with almost the same density as water that remain suspended. Larger or heavier particles such as algae, bacteria, aquatic animals and silt will eventually settle to the bottom, although some of these may actively swim or possess flotation devices to counter the effects of gravity. These living particulates are addressed separately below.

Inorganic particles are relevant to aquatic plants and algae because they can contribute nutrients that have been adsorbed on the particles. In addition, they can accelerate the process of filling the lake to the point where a shallow, soft and nutrient-rich bottom is widely available for rooted aquatic plant growth. Most inorganic particulates will have originated from terrestrial sources, although wave action and human activity can stir up lake bottom sediments and redeposit them. Organic particles, sometimes referred to as detritus, are living or dead biota - plants, animals and bacteria. These eventually settle to the bottom where they decompose and release their nutrients.

Bacteria

Although never seen by most people, bacteria play a pivotal role in the life of lakes. They are the most abundant group of organisms in a lake and most of them are critical in converting any organic material to inorganic form. They may be free-floating in the water column, attached to a substrate or in the sediments. Many are aerobic, requiring oxygen for the conversion of organic material to inorganic forms and energy. Many others are anaerobic, using other chemical pathways to derive energy. One such group, the sulfate reducing bacteria, is instrumental in converting inorganic mercury to the highly toxic organic form, methyl mercury, as a byproduct of their growth. Some bacteria are photosynthetic (e.g., cyanobacteria, also called blue-green algae). Some bacteria create human health problems or have proven to be useful indicators of the likely presence of threats to human health. *Escherichia coli* is usually an innocuous bacterium found in our intestines, but its abundance in a lake indicates sewage, septic inputs or other fecal contaminants and the potential for the transfer of human bacterial and viral diseases.

Algae

Algae are mostly microscopic plants that may be free-floating (phytoplankton) or attached to a substrate (periphyton). They may be single-celled or have many cells. In a moderately rich lake, there could be nearly one hundred species of algae in a tablespoonful of lake water. In a eutrophic lake, there may be millions of cells in a gallon of water. Algae are divided into several major groups, principally based on the relative combination of photosynthetic pigments and characteristics of the cell wall, food storage form, and flagella, but each group has particular characteristics that often contribute to lake problems.

The blue-greens are evolutionary intermediates between heterotrophic bacteria and algae. They are considered to be bacteria (Cyanobacteria) with the photosynthetic pigment, chlorophyll. Blue-greens often form nuisance blooms, appearing like thick green paint on the lake's surface and causing taste and odor problems in drinking water. Many blue-greens, particularly certain troublesome species, have the ability to "fix" nitrogen. While other algae must obtain their nutrients from dissolved inorganic (nitrate, nitrite, and ammonia) or organic nitrogen in the water, these blue-greens can use atmospheric nitrogen that is dissolved in the water. A shortage of inorganic and organic nitrogen can give nitrogen-fixing blue-greens a competitive edge, and they use other characteristics (flotation) to maintain it. Many of them have a gelatinous sheath that makes them undesirable to microscopic grazers. Three genera of blue-greens are so commonly associated with problems in lakes that lake managers have given them nicknames: Annie for *Anabaena*, Fannie for *Aphanizomenon* and Mike for *Microcystis*.

Conversely, diatoms are rarely problems in recreational lakes and usually form an important part of the food chain. They construct silica shells of many shapes with intricate markings. A hundred years ago, it was quite the fad to view slides of different diatom shells in elaborate displays. Electron microscopy has made the view even more spectacular. Despite their glass shells, these algae are easily eaten by small aquatic animals called zooplankton. Common planktonic diatoms include *Asterionella*, *Fragilaria*, *Tabellaria, Aulacoseira* and *Cyclotella*. Other chrysophytes ("golden" algae) live in shells that look like wine glasses or spiny coats with whipping flagella to move them about. Some of these non-diatom chrysophytes can cause taste and odor problems in drinking water reservoirs, but are rarely a problem in recreational lakes.

Green algae (Chlorophyta) are an incredibly diverse group ranging from single-celled to complex multicellular organisms that may be on the main evolutionary line to vascular plants. They are important constituents in the food chain, but some species can cause blooms in eutrophic lakes. They generally prefer a higher ratio of nitrogen to phosphorus than blue-green algae.

The dinoflagellates (Pyrrophyta) tend to be less abundant than the above groups but are interesting because some of the dinoflagellates cause harmful algal blooms in marine environments. Freshwater forms are not known to be toxic, but are often associated with high organic content waters. Cryptomonads, a related group of flagellates, are capable of photosynthesis but may prey upon bacteria. Because all are motile, they can often dramatically change their position in the water column to take advantage of local conditions. Often, they are found at the top of the thermocline where sinking organic material is slowed by the denser water but light is still sufficient. Euglenoids are another mostly flagellated group that share pigment composition with the green algae, but make use of organic particles and dissolved compounds more like the dinoflagellates and cryptomonads. They can form surface scums that vary in color from green to red, and at high abundance are normally indicators of very poor water quality.

Most other algal groups are relatively rare in freshwater lakes and occur mainly in marine environments (i.e., red and brown algae). Each of the above groups has species with characteristics that may allow them to become very abundant and troublesome. Sometimes, knowing which species is in “bloom” can help understand the cause of the bloom. For example, certain blue-green algae often bloom when phosphorus is abundant and nitrate is low because they can fix nitrogen from dissolved air. They often prefer a period of calm water because they float and consequently shade out competing species. The concurrence of these conditions will usually result in blue-greens, but the absence of one element may shift the balance to another species or another algal group. The diatoms tend to prefer times of high mixing, cooler temperatures and higher silica availability - conditions found at spring and fall turnover. Many dinoflagellates seem to prefer conditions with above average organic material.

The dynamics of the thermal, light and nutrient regimes in lakes cause a fairly predictable pattern in the seasonal succession of algal species (Figure 5), but there may be surprises at any time. Typically, though, spring and fall turnover favor the diatoms which may become very abundant but usually do not cause severe impacts on human use, although some species cause taste and odor problems in drinking water reservoirs and can clog filters. After thermal stratification, green algae often become dominant for most of the summer when nitrogen is available, but they may be replaced by blue-green algae at higher temperatures, lower nitrogen concentrations, and high pH.

Because there are so many species of algae and identification requires considerable expertise, limnologists have developed surrogate measures of algal biomass. One of these is to measure the chlorophyll that all algae share, chlorophyll *a*. Chlorophyll *a* can be measured very accurately and quite easily. Unfortunately, the correspondence between the amount of chlorophyll and the actual biomass of algae is somewhat variable. Not all algal species have equal amounts of chlorophyll per unit volume and the amount of chlorophyll in each species varies with the nutritional health of the cells. Nevertheless, chlorophyll has become a reliable and useful measure for lake management. A second, less closely related measure of algal biomass is Secchi disk transparency. It involves lowering a black and white disk into the water and recording how far down it remains visible (Figure 6). Visibility has been reasonably well related to chlorophyll and forms a part of lake assessment that almost anyone can accomplish.

Aquatic Macrophytes

As opposed to algae that are usually microscopic plants, these are large aquatic plants, easily visible to the naked eye. In shallow lakes with soft bottoms, the vast majority of lakes in Massachusetts, these are often the most abundant plants. Algae and macrophytes often compete for light, so it is unusual to find both as problems in any particular lake, although it does happen. Macrophytes may be rooted or free-floating, although most are rooted (Figure 7). They may also be submergent, emergent, or floating-leaved. There are many taxonomic groups but the above categories are often the most useful for understanding the causes of a macrophyte problem and determining an appropriate management strategy. In fact, within each category, many species may look very similar as their growth habit responds to common lake conditions. However, even though many macrophyte species appear similar, their propensity to cause problems in lakes varies. Effective management of macrophytes usually requires species identification. For example, a drawdown may reduce densities of fanwort (*Cabomba caroliniana*) but may increase densities of naiad (*Najas flexilis*) based on their overwintering strategies (vegetative vs seeds).

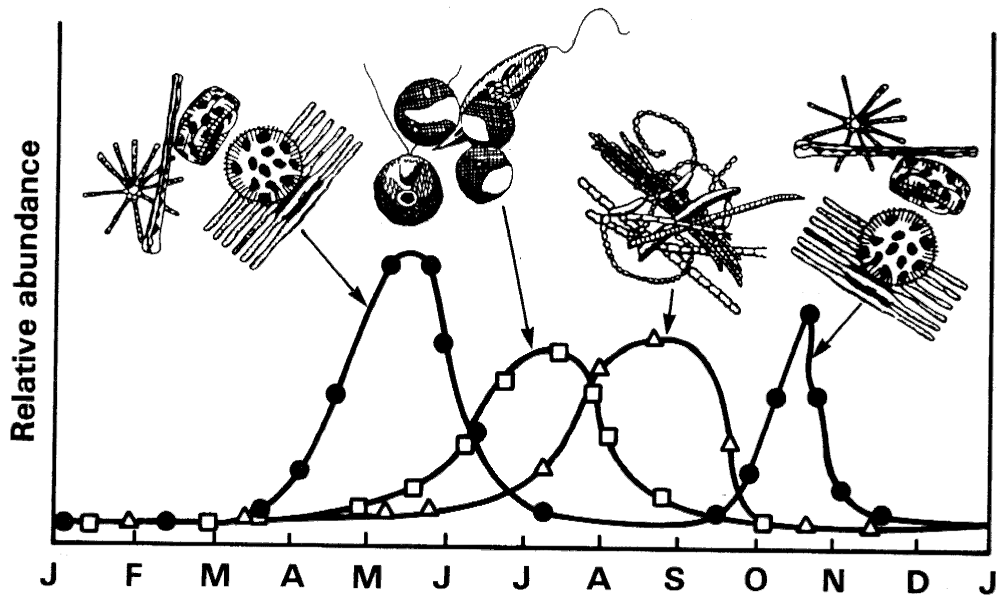

Figure 5. Seasonal Succession of Phytoplankton (Olem and Flock, 1990)
Diatoms tend to dominate in spring and fall, with greens and blue-greens dominant during summer, but many variations are possible.

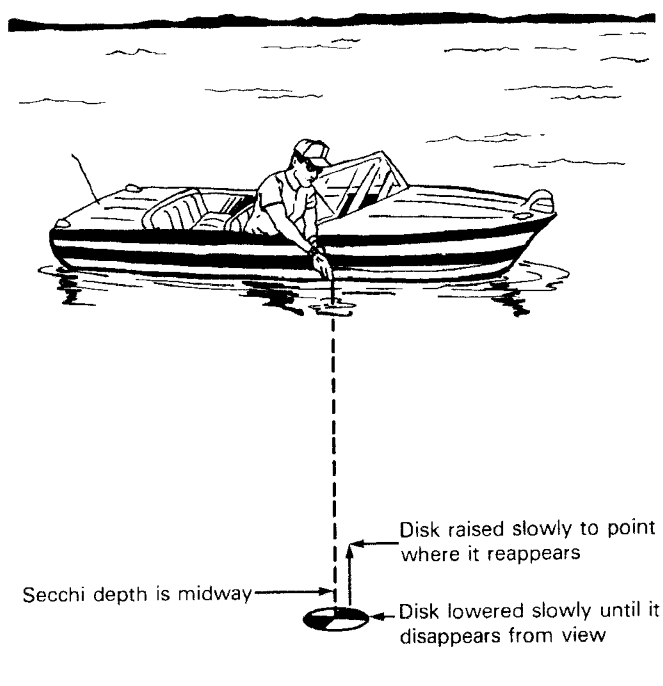

Figure 6. Measurement of Secchi disk Transparency (Olem and Flock, 1990)

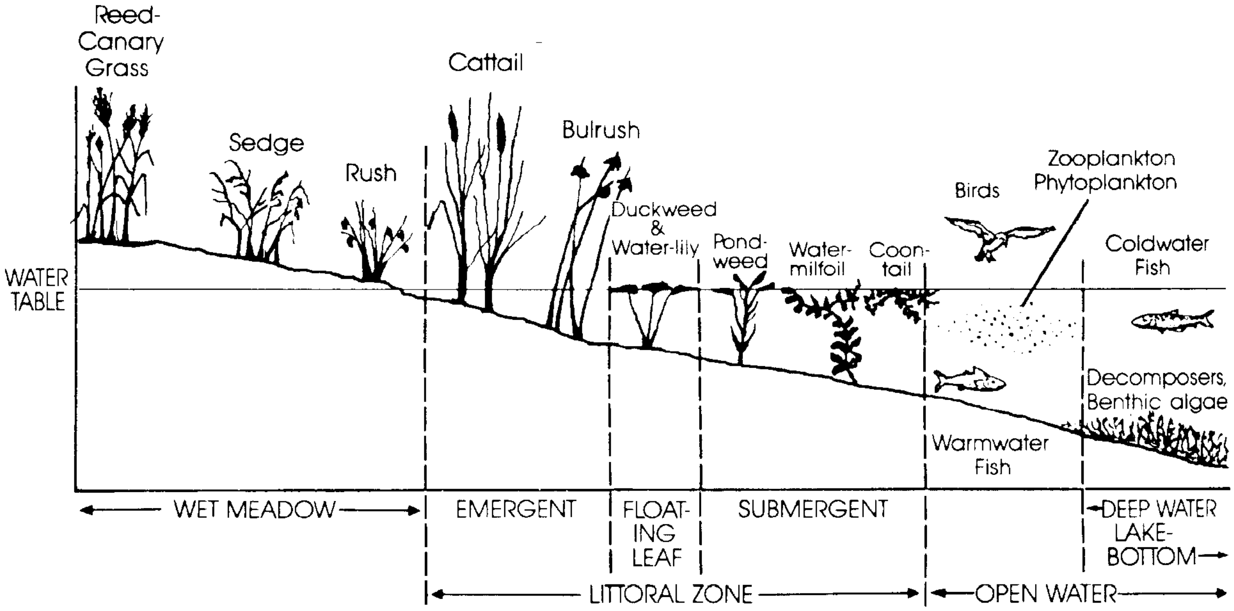

Figure 7. Typical Aquatic Plant Zones in Lakes and Ponds (From Kishbaugh et al., 1990)

Table 1. Introduced Species Known to Create Nuisance Conditions in Massachusetts

Scientific Name	Common Name
Cabomba caroliniana	Fanwort
Egeria densa	Brazilian elodea
Hydrilla verticillata	Hydrilla
Lythrum salicaria	Purple loosestrife
Marsilea quadrifolia	Pepperwort
Myriophyllum aquaticum	Parrotfeather
Myriophyllum heterophyllum	Variable watermilfoil
Myriophyllum spicatum	Eurasian watermilfoil
Najas minor	Spiny naiad
Nelumbo sp.	Lotus
Nymphoides peltatum	Little floating heart
Phragmites sp.	Reed grass
Trapa natans	Water chestnut

Rooted aquatic plants typically grow from a root system embedded in the bottom sediment. Unlike algae, they derive most of their nutrients from the sediments just like terrestrial plants, but they may be able to absorb nutrients from the water column as well. Because they need light to grow, they cannot exist where the lake bottom is not exposed to sufficient light. The part of a lake where light reaches the bottom is called the photic zone. For many plants, nutrients in the sediments may be in excess and growth is limited by light, particularly during early growth when the plant is small and close to the bottom. Emergent plants solve the light problem by growing out of the water, but that limits them to fairly shallow depths. Free-floating plants also are not limited by light, except in cases of self-shading when growths are dense, but cannot use the sediments as a source of nutrients. Finally, floating-leaf plants have attempted to achieve the best of all worlds by having their roots in the sediment and leaves at the surface, but they still have depth limits.

Introduced Plant Species

A subset of aquatic macrophytes, these plants tend to have high nuisance potential. As a gateway for settlement of the country and as part of the modern trans-world travel network, Massachusetts is highly susceptible to introductions of non-native species. Recently introduced species, unlike the natural biota and even the non-native biota introduced more than a hundred years ago, have few or no enemies, and are often invasive pests that can totally dominate and eliminate native populations. They are easily introduced in a variety of unwitting ways, most notably through the aquarium and horticulture trades, with dispersal among lakes by boats. Waterfowl are also important vectors. In many situations where a non-native species has been introduced, a near monoculture of that species develops, reducing recreational utility and habitat value.

Introduced non-native species can displace a healthy and desirable aquatic community and produce economically and recreationally severe impacts even though no other change has occurred in the watershed. The introduction of a non-native and undesirable species can result from the actions of a single person who does not realize the eventual impact and may not be aware that he/she has introduced the non-native species.

Consider some examples. Introductions of Eurasian watermilfoil (*Myriophyllum spicatum*) in Lake Champlain (Vermont/New York), Lake George (New York), Okanagan Lake (British Columbia) and many lakes in Massachusetts and other states threaten otherwise healthy lakes. Within just a few years, a small patch of the introduced species can grow to fill the lake, top to bottom, within the photic zone. Another nuisance species, fanwort (*Cabomba caroliniana),* is a popular aquarium plant and may have been introduced from freshwater aquariums. Purple loosestrife, a beautiful non-native wetland plant, completely crowds out native species and creates stands so dense that wildlife habitat is degraded. It was introduced by horticulturists and gardeners. There are many non-native species of concern, not all as invasive as these examples. In most cases, they demand special attention. While an overabundance of native species and diminution of desired uses can be managed over time, introduced species generally require quick action if eradication is to be achieved. The environmental cost of delay is usually higher than the risk of immediate use of most control options. The quicker the response, the smaller the degree of intervention needed to protect the environment. It may be difficult to impossible to actually eradicate an invasive species, but the probability of achieving and maintaining control is maximized through early detection and rapid response.

The Massachusetts Department of Environmental Protection developed a database of non-native (i.e., introduced) aquatic plants based on surveys in 1993-94. The database does not represent a comprehensive listing of all lakes with non-native species, but is considered representative of conditions at the time. Of the 320 lakes surveyed, 64% had non-native species. The most commonly observed non-native species in these surveys were *Myriophyllum* (milfoil), *Cabomba* (fanwort) and *Lythrum* (loosestrife).

No non-native species were found in 115 of the surveyed lakes, although there is some debate as to how long a species must be present to be considered "native". Variable milfoil (*Myriophyllum heterophyllum)* is not native to Massachusetts or New England, but remains a potential nuisance species. Likewise, some species of *Phragmites* are considered native but may still be invasive. Some species not found in the 320 surveyed lakes are known from other Massachusetts lakes now, most notably *Hydrilla* in one Cape Cod lake and *Myriophyllum aquaticum* in another Cape Cod lake. All of the species listed in Table 1 have been found in Massachusetts as of 2002, and the frequency of most has increased since the 1994 listing. DCR staff updated the earlier DEP survey for most of these lakes through 2003 (see Appendix VI of the GEIR).

Native Plant Species

In general, a healthy native plant community is considered desirable for a lake. Where the sediment is suitable and light penetrates, rooted plants will grow. The question is not whether or not rooted plants will be present in most lakes, but rather what types and at what density. A diverse assemblage of species indigenous to the area will in most cases not constitute a nuisance to people, and will provide valuable habitat. Invasive species, often defined as non-native or introduced forms, have a tendency to dominate the plant community as a consequence of competitive superiority and/or low loss rates to herbivores (plant eaters). In theory, a native assemblage will be more balanced. However, some native species can become "invasive", expanding into areas either not previously colonized or at one time occupied by other native species. Such imbalances can lead to nuisance conditions, as with dense coverage by water lilies (*Nymphaea* or *Nuphar*) or watershield (*Brasenia*). Submergent growths of naiad (*Najas*) or coontail (*Ceratophyllum*) can become too dense, break free of the sediment, and become nuisances to boaters or swimmers. Native plant communities may therefore require management to remain in balance.

While the management of introduced species often focuses on eradication (which is itself a very difficult task), management of indigenous species with nuisance potential tends to favor control only to the extent necessary to restore balance. This may require ongoing maintenance, and it is generally true that rooted plant management is likely to require repetitive actions over a prolonged time period.

Aquatic Animals

Plants provide the habitat and food for many forms of animal life ranging from microscopic rotifers that filter tiny algae, to zooplankton that hunt larger algae, to insects, to fish and aquatic mammals that eat even larger plants or animals. A change in any part of this trophic web ripples throughout the system in subtle or even dramatic ways. As a very simplified example, consider the classic four level trophic system. Certain algal species may be preyed upon by zooplankton. Zooplankton are preyed upon by planktivorous fish species such as golden shiners (*Notemigonus crysoleucas*) that are then preyed upon by larger piscivorous species such as largemouth bass (*Micropterus salmoides*). Reducing the algal population by some other form of control may also reduce the zooplankton, the planktivorous fish and the piscivorous fish. Conversely, adding more piscivorous fish or increasing their ability to find their prey may reduce the planktivorous fish and reduce predation on zooplankton. The zooplankton can then increase in abundance and reduce algal biomass. Usually, the interrelationships are much more complicated, and it is generally difficult to predict the outcome. For example, increasing piscivorous fish may increase zooplankton predation on edible algae but give relatively inedible algae (e.g., blue-greens) an advantage. Loss of algae may promote macrophyte growth and provide shelter for planktivores, reducing piscivore impacts. Variability in biological response to management tends to be high.

Alterations, even temporary ones, may have serious effects on the biota. For example, one of the most critical periods in the life history of fish is during spawning. Some lake management practices may be relatively benign except when they coincide with the spawning period for fish that occur in the lake. Depending on the species, fish spawning generally occurs in spring or fall (Table 2). Care must be taken to evaluate possible impacts of the timing and magnitude of lake management actions.

Table 2. Spawning Conditions for Common Massachusetts Fish Species (after Everhart et al., 1975)

Species	Spawning Time	Site	Method
Yellow Perch *Perca flavescens*	Early spring	Brush, aquatic plants	Deposited "rope" of eggs, usually on vegetation
White Perch *Morone americana*	Late spring	Sand or gravel bottom	Egg scatterer
Bluegill *Lepomis macrochirus*	Early summer	Littoral zone	Parental care; nest is a circular depression
Pumpkinseed *Lepomis gibbosus*	Summer	Littoral zone	Parental care; nest is a circular depression
Largemouth Bass *Micropterus salmoides*	Late spring	Littoral zone	Parental care; nest is a circular depression
Smallmouth Bass *Micropterus dolomieui*	Spring, early summer	Gravel bottom	Nest builder
Brown Bullhead *Ameiurus nebulosa*	Late spring	Littoral zone	Crevices or nests
Chain Pickerel *Esox niger*	After ice out	Littoral zone	Eggs scattered among vegetation in shallow areas
Lake Trout *Salvelinus namaycush*	Oct-Dec.	Sand or gravel bottom	Eggs scattered over gravel
Brook Trout *Salvelinus fontinalis*	Sept.-Dec.	Gravel bottom of tributaries	Deposited in "redd" or nest
Brown Trout *Salmo trutta*	Fall	Gravel bottom of tributaries	Deposited in "redd" or nest
River Herring *Alosa aestivalis* (Blueback) *Alosa psuedoharengus* (Alewife)	Spring	Sand or gravel bottom	Egg scatterer

Note that some animals are also introduced, ranging from many fish species stocked for angling purposes to invertebrates that may represent major disruptions of energy flow in the aquatic food web. Angling is a major lake use, and a major role of the Department of Fish and Game is managing lake fisheries for the enjoyment of the angling public, but many of the fish in our lakes today are not native to the area. Both largemouth and smallmouth bass and both brown and rainbow trout are introduced species. Many baitfish species have been introduced as well, either intentionally to form a forage base for growing gamefish or accidentally as escapees from bait buckets. It was a common management practice in the late 1800s and first half of the 1900s to move fish from lake to lake, introducing a range of species to each lake and allowing "nature" to decide what would become abundant. It was also common to "reclaim" a lake (poison the existing fish and restock) when fishing was considered very poor over an extended period of years, usually as a consequence of overabundant panfish. Stocking is much more focused and tightly controlled these days, and is part of the overall management plan for many lakes and regions of the Commonwealth. Reclamation by poisoning is no longer practiced in Massachusetts.

Other possible introductions of greater concern include zebra mussels (*Dreissenia polymorpha*) and various non-native relatives. These bivalve molluscs (small freshwater clams) can out-compete all other molluscs, cover rocks, docks and other hard substrates, and filter the water to the extent that the open water food web may collapse. Zebra mussels have not been found in Massachusetts as of this writing, but are known from the region and pose a great threat to water supplies and recreational lakes, as well as to the overall ecology of lakes. Non-native zooplankton, crayfish, and other invertebrates threaten native biodiversity, but as of yet have not proven to disrupt overall lake ecology in Massachusetts. This is probably more a matter of lack of study than lack of impact.

LAKE MANAGEMENT PLANNING

The Lake Management Plan

Developing a lake management plan is a useful and necessary process to select and guide the implementation of complex management techniques. It may not be absolutely necessary in all cases, but is always appropriate for setting overall management goals and laying out the techniques that will be used to achieve those goals. Small projects, such as the installation of benthic barriers around a boat launch or swimming area, do not require a detailed lake management plan, but at a lakewide scale, such application would benefit from such a plan. In some cases it may not make sense for a town or state agency to develop a detailed plan for a system which they do not control unless cooperation of other towns, agencies or landowners is obtained. However, having the framework of a plan in place may facilitate that cooperation, and development of management plans by multiple towns in a watershed is encouraged.

The flow chart in Table 4 shows the process of developing and implementing a lake management plan and the parties that should be involved at each step. Like any sound construction, the foundation must be secure before the next level can be supported. That is, an error at the beginning will magnify throughout the entire process. When developing a lake and watershed management plan, it is very important to keep in mind that:

- **Not all plans need to have each of the components fully developed, and depending on the management issues, plans may not need to address some of the components at all**. Carefully consider resources and uses when prioritizing plan elements.
- **The size and detail of the plan should reflect the complexity of the lake and its management issues**. In general, a plan may range from a couple of pages for a small privately owned pond to several hundred pages for a large public lake with many uses and management issues.
- **The outline presented here provides a menu of options, but should not necessarily be adopted verbatim**. Elements and options are best evaluated in consultation with an experienced lake management professional.

As a general rule, having thorough data for these components will enable the production of a more valuable lake and watershed management plan and will increase the likelihood of successful protection and/or restoration of the water body. The other general rule is that the greater the potential impact or expense of a proposed management technique, the greater is the need for complete information. The common elements of lake management plans can be summarized as follows:

- **Problem Statement**: List issues/problems that should be addressed. Why is management action under consideration, and what previous reports, data, historic management actions and past recommendations support this need?
- **Management Goals:** Get public input by all stakeholders to provide a concise statement of goals, desired future uses and characteristics. Goals should be specific, measurable, and realistic/feasible.
- **Watershed and Lake Characteristics**: Include maps of watershed boundary, watercourses, drainage systems, geology, topography, soils, land use, any zoning, and pollutant sources. Provide maps of lake bathymetry and sediment types/depth. Collect data for hydrology and water quality and construct nutrient budgets. Model the system to the extent practical and necessary to predict results of management actions. Collect data for bacteria, algae, vascular plants, zooplankton, invertebrates, fish, reptiles, amphibians, birds and mammals, and check available maps and records for protected species.
- **Past In-Lake Management Techniques**: Review all physical, chemical and biological controls, and any other in-lake management techniques that have been implemented.

- **Existing Watershed Management Techniques:** Review all regulatory (e.g., zoning, resource protection bylaws, health statutes) and non-regulatory (i.e., educational, procedural and structural) management techniques that are in place and being used within the watershed.
- **In-Lake and Watershed Management Alternatives:** Evaluate options for feasibility, impacts, costs, and effectiveness to attain the goals.
- **Management Recommendations:** Include both short- and long-term management options for in-lake and watershed management, with time frames. Preventive and mitigative measures should be included. A description of the monitoring and evaluation process to be used for all proposed actions should be included, with pre- and post-management elements.
- **Plan Approval:** Present the plan at one or more well-publicized public meetings, and offer an opportunity for comment.
- **Implementation:** The five phases to implementation (funding, design, regulatory review, construction or application and follow up monitoring and evaluation) will be lake- and community-specific, but may involve considerable interaction with outside agencies and consultants.

The lake management plan represents the assimilation of all the previous steps into one understandable written document describing long-term goals for the lake and ways to achieve those goals, along with their ecological and financial consequences. If properly developed, it should be useful for a long time, modified as more is learned about the lake and progress is made.

Most plans focus on mitigating perceived problems, but protection will almost always be essential to maintain desirable qualities. Some lake users may perceive that a lake meets most of its intended uses and is unlikely to change, but lakes are dynamic systems prone to change even without human interference. A “hands off” approach can not be expected to preserve key qualities of the lake system, although knowing when not to take action can be as important as knowing what techniques to apply and when. It will be no less important for all of the lake management plan development steps to be followed for lakes to be protected than it is for lakes with serious problems.

All the steps of management planning can be difficult, but do not underestimate the importance of the early steps. The problem statement serves to clarify user perception of the problem and to distinguish between perception and reality. As stated earlier, individual lakes fall along a continuum of lake evolution from pristine, nearly sterile bowls of water to shallow, productive wetlands; all are natural states. Public perception also varies along a continuum with every individual preferring a slightly different view of a lake. Public perception may be in sharp conflict with the natural state of a lake and with a realistic expectation of what can be accomplished. The development of a problem statement is eventually a reconciliation of perception with reality. Reality in this case is determined by water quality monitoring and watershed evaluation, the latter being the tool to differentiate between human impacts and the natural state to the extent possible. At this early stage, it is imperative to involve as much of the community as possible in management planning. All subsequent steps will be easier if the chosen plan has broad community support created by participation in the plan’s development coupled with a realistic expectation of what can be accomplished.

With the previous steps in place, evaluation of possible management strategies becomes a focal point for the plan. A number of the diagnostic tools permit limited cost/benefit analysis. This review is principally focused on defining procedures acceptable in Massachusetts for the implementation of lake management controls. It recognizes that there are appropriate short-term strategies that are steps along the path of a long-term strategy. There may be short-term strategies that merely attempt to maximize human resource usage without significantly changing the natural state of a lake. Long-term strategies may have limited impact in the short-term but may eventually produce the closest approximation to a sustainable and healthy lake condition, maximize human resource use and may be more cost-effective. The appropriate choice will depend on community priorities, regulatory restrictions, specific characteristics of the lake, community resources and the effectiveness, adverse impacts and costs of the available lake management techniques. This is admittedly a lot to consider all at once, but effective lake management is rarely a simple process.

As described, implementation appears to be the last step. It is actually part of a cycle of assessment and action, but does normally require the prior steps to be successful. However, for many previous implementation projects, it was almost the only step. The importance of completing the previous steps in arriving at an acceptable and successful implementation phase cannot be overemphasized. These steps can promote community support, develop funding and minimize the effort required to continue implementation in successive years.

This review, within the limits of available science and experience, attempts to describe management techniques that have been applied in Massachusetts and have a high probability of success under appropriate conditions. Lake management controls applied in accordance with this review have a reasonable chance of success, based on our present knowledge. Controls that are not covered by this review either have a seriously limited chance of success (often with major negative impacts) or represent a change in scientific knowledge and experience since this report was written. In the latter case, the burden of proof must fall on those proposing the strategy. However, regulatory agencies need to keep up with the science and recognize the value of experimentation in lake management. Few impacts to lakes are irreversible, and few targeted benefits can be achieved without at least temporary impact to some untargeted resources. Successful lake management requires balancing varied and sometimes competing interests.

Predicting the Outcome of Management

Knowing exactly how an aquatic system and all its inhabitants will respond is not usually possible; uncertainty is a fact of life, especially in lake management. The direction of anticipated change and the general magnitude of change can be predicted, however, at least for water quality and algae-related features of lakes. For management aimed at controlling nutrients to minimize algal blooms, many studies of watersheds have produced scientific literature statistically comparing nutrient inputs with average lake nutrient concentration, average chlorophyll concentration and Secchi disk transparency. Knowledge of any one of these parameters provides a rough estimate of all the others for relatively large, stratified north temperate lakes without dominant rooted plant growth. For other lakes, particularly lakes with abundant plant growth, these “empirical” models will not work as well and may not work at all, but we rely on them to make general predictions of lake response to nutrient controls.

Quite a few of these models have been developed; all are remarkably consistent and suggest that the general models are robust even though the confidence one can place in a specific prediction for a particular lake is limited. The details of the many available models and how to use them is beyond what this guide is intended to cover, but the ultimate goal is to understand how nutrient loading relates to lake attributes that affect lake uses.

Water clarity is often a key determinant of satisfaction with the appearance of a lake, and exhibits a strong curvilinear relationship with phosphorus (Figure 8). A change at low total phosphorus levels results in a much larger change in transparency than the same absolute change at a higher total phosphorus level. There is, however, considerable variation possible at any phosphorus level. The sources of variability can be very important to management decisions, and include the nature of the zooplankton community, the availability of phosphorus, and other sources of turbidity (such as suspended inorganic sediment). It is very difficult to predict exactly how a change in phosphorus loading will affect the clarity of an individual lake without considerable information on these other sources of variation in the relationship.

A variation on this approach is to use the empirical models to develop an index that can be related to perception of trophic state. One of the most widely used of these indices is Carlson’s Trophic State

Index (TSI). Knowing the total phosphorus, chlorophyll *a*, or transparency, one can calculate the TSI. The TSI scale ranges from 0 to 100 with each 10 units of increase representing a doubling in algal biomass. Unlike the measurements of nutrients or chlorophyll, the TSI has been related to problem perception (Figure 9). The primary value of the TSI will be in presenting comparative information to decision-makers in an easy to visualize, non-technical form.

Increasing levels of modeling sophistication are warranted when the choices to be made based on modeling results carry major costs. It is quite appropriate, however, to use simpler models to generate results for potential management scenarios for comparative purposes and to elucidate the level of management needed. It is extremely frustrating to conduct a program to reduce nutrient loading by 50%, only to find that no visible change in water clarity is gained because the system was out in the right hand portion of the graph in Figure 8 (high P, low clarity). It is very helpful to know the general order of magnitude of the loading reduction needed to meet program objectives before embarking on a load reduction campaign. Exact numerical predictions from models should not be believed in most cases, but the models do reliably indicate the direction and approximate degree of change to be expected.

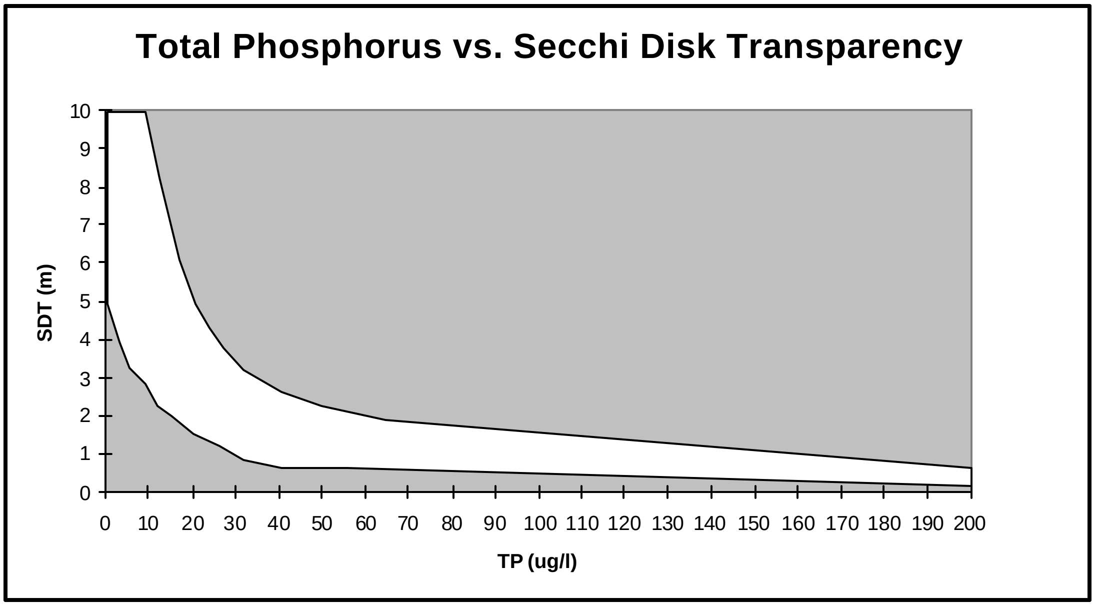

Figure 8. Expected Range of Water Clarity with Changing Phosphorus Concentration.

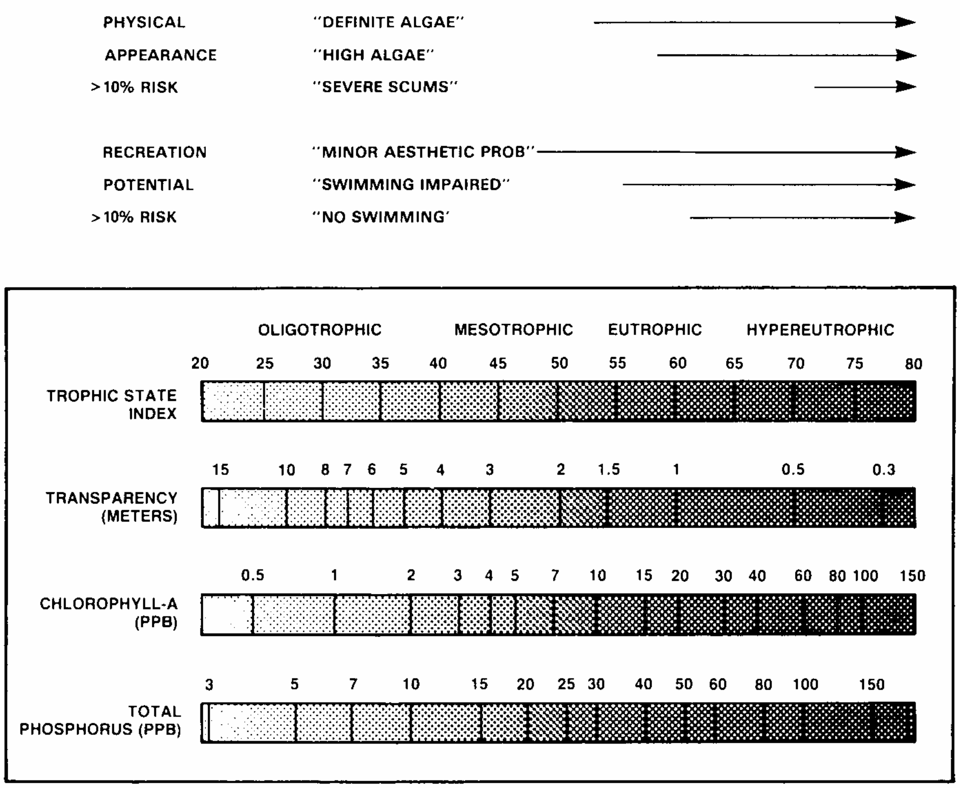

Figure 9. Carlson's Trophic State Index Related to Perceived Nuisance Conditions (Heiskary and Walker, 1987). **Lengths of arrows indicate range over which a greater than 10 percent probability exists that users will perceive a problem.**

TECHNIQUES TO MANAGE EUTROPHICATION AND AQUATIC PLANTS

Overview of Options

The GEIR and this Guide break up management options into two general categories: control of nutrients and control of aquatic plants. Control of nutrients is usually intended to reduce algal growth; it may prevent non-rooted vascular plant growth as well, but will not typically control rooted aquatic vegetation. Nutrient controls may occur in the watershed or in the lake, but if watershed controls are inadequate, in-lake controls will provide only temporary relief. Direct control of aquatic plants (vascular plants or algae) is often performed on a maintenance basis, but in some cases the community can be altered in more permanent ways.

One of the most effective ways to control algal populations is by limiting the nutrient supply to the lake, and thus limiting growth of algae. Phosphorus is the best nutrient to control, and the nutrient control options will deal primarily with phosphorus control. Even in cases where lakes are limited by nitrogen, phosphorus control is still the preferred method to control algae. In nutrient rich lakes, the growth of algae may be limited by light, and reduction in nutrient concentrations may not have a significant effect until the nutrient concentrations are lowered sufficiently to induce nutrient limitation.

One must identify the sources of nutrients before an effective control strategy can be determined. Once the relative importance of the sources of phosphorus is determined, one can examine the control techniques identified below for applicability and feasibility:

- Non-Point Source Management – control of diffuse nutrient sources from the watershed
- Point Source Management – control of point sources, usually piped discharges
- Hydraulic Controls – diversion, dilution, flushing, and hypolimnetic withdrawal strategies
- Phosphorus Inactivation – chemical binding of phosphorus to limit availability
- Artificial Circulation and Aeration – mixing and oxygen addition
- Dredging – removal of nutrient-laden sediments
- Bacterial Additives – encouraging uptake of nutrients by non-algal microbes
- Removal of Bottom Feeding Fish – elimination of major recyclers of nutrients

The needed or expected reduction in phosphorus loading should be modeled to predict the change in trophic status. In general, algal problems will be minimized at loadings less than Vollenweider's (1968) permissible level, which is a calculated value dependent mainly on the depth and hydraulic residence time of the lake. Yet algal abundance in response to nutrient loading is a probability distribution, not a threshold function. Consequently, algal blooms may be expected at some reduced frequency, even at fairly low nutrient levels, and lakes will not respond identically to changes in loading. Acceptable results might be achieved at loadings higher than the permissible level, but unacceptable conditions can be expected where loading exceeds Vollenweider's (1968) critical limit. Managers should be prepared to adjust strategies in response to resultant lake conditions; algal control through nutrient limitation is often an iterative process.

Additional ways to directly limit the density of algae may be needed on an interim or supplemental basis, and include the use of biocidal chemicals, dyes or biocontrol agents. Likewise, many aquatic vascular plants will not be controlled by nutrient reductions, and direct control techniques will be necessary. Direct rooted plant management options include physical, chemical and biological techniques as noted below:

- Drawdown - lowering of the water level to dry and freeze susceptible vegetation, with limited potential to control algal growth
- Harvesting - multiple methods of mechanical plant cutting, with or without removal, and algal collection

- Biological Control - biomanipulation, the practice of altering biological communities to control algae or macrophytes through biological interactions
- Benthic Barriers - placement of materials on the bottom of a lake to cover and impede the growth of macrophytes
- Herbicides and Algaecides - introduction of biocidal chemicals to directly kill vascular plants and/or algae
- Dyes and Covers - addition of coloring agents or sheet material to inhibit light penetration and reduce vascular plant and algae growths
- Dredging - removal of sediment and associated plants to inhibit growth
- Sonication – use of sound waves to disrupt and kill algal cells

In the case of nuisance species, especially introduced forms considered to be invasive, prevention is at least as important as management of existing infestations. Preventing the introduction of non-native plants is obviously the most desirable management option, but often this fails. One of the most active routes of introduction is the aquarium and landscaping trades; many of our greatest nuisance aquatic species can be traced to introductions by these commercial routes (Les, 2002). The need for laws and enforcement relating to such introductions remains great. This manual focuses on remediation for excessive macrophyte growths, and does not explicitly address approaches for prevention. However, as it is extremely difficult to truly eradicate introduced species, much greater emphasis is needed on controlling the undesirable spread of species by human actions.

A summary table of possible techniques for algae (and non-rooted vascular plant) control is presented in Table 4 and options for rooted plant control are summarized in Table 5, both adapted from Wagner (2001). All techniques have associated benefits and drawbacks, and those contemplating plant management should familiarize themselves with the following axioms for algae and vascular plant management:

Axioms for the Control of Algae in Lakes

1. Where light and nutrients are sufficient and toxic substances are limited, algae will grow
- Phosphorus >0.01 mg/L and nitrogen >0.3 mg/L can support blooms
- Phosphorus >0.05 mg/L and nitrogen >1.0 mg/L will usually support blooms
- Very little light is necessary for some species of algae to bloom; normal daylight is adequate except at very high algal densities
- Metals and some organic compounds are the primary toxicants for algae

2. One factor will control the abundance of any given alga, but that factor can vary over time and among algae
- Some blue-greens can fix nitrogen, but require elements not needed by other algae
- Succession of algae may be triggered by changing control factors
- Control of the whole algal community by one factor occurs at extremes (e.g., low P or high Cu)

3. Nutrient ratios are major determinants of the type of algae present
- N:P:Si ratio is most influential, but trace nutrients can have an effect as well
- Blue-greens which can fix N thrive at low N:P ratios, while most greens prefer high N:P ratios
- Diatoms require high Silica
- Carbon can be important at very high N and P
- Light can also be an important determinant of algal assemblage composition

4. Productivity and biomass are related but separate concepts
- Productivity is a growth process
- Biomass is the net result of growth and loss processes
- High productivity leads to high biomass if loss processes are not adequate to maintain balance

5. Diversity of algal adaptations may defeat controls other than maintaining low phosphorus
- N fixation by blue-greens minimizes N limitation
- Buoyancy regulation allows vertical movement
- Auxiliary pigments assist in low or high light habitats
- Heterotrophy can sustain some algae
- Anti-grazing mechanisms can minimize zooplankton impacts
- Copper resistance by some algae limits control options with algaecides

6. The most effective algal control is achieved through reduction of external and internal phosphorus loading
- P can be made to limit productivity most reliably
- Essential to determine relative magnitude of sources of P
- May require multiple techniques and extended timeframe

7. High grazing pressure yields the lowest algal biomass per unit of fertility
- Large-bodied, herbivorous, zooplankton (*Daphnia*) at high biomass can limit algal biomass
- Algal adaptation can overcome grazing pressure if nutrients are sufficient

8. Algaecides should only be used until growth processes can be controlled
- Algaecides can provide short-term control and can prevent blooms if applied at the proper time
- Algaecides rarely provide long term control and can have adverse side effects

Axioms for the Control of Rooted Plants in Lakes

1. In lighted areas with suitable sediments, plants will grow
- Light and substrate are critical factors
- A desire for no plants demands a maintenance program
- Management for a diverse native community is encouraged

2. No amount of watershed management will control an existing infestation
- Rooted aquatic plant growths are not controlled by clean water
- Increased water clarity may extend plant growth
- Watershed management complements in-lake management

3. Understanding plant biology and ecology is essential to control
- Native vs. non-native species differences exist
- Reproduction by seeds vs. vegetative propagation is important
- Monocotyledon vs. dicotyledon biology may affect results
- Light and nutrient needs vary substantially among plant groups

4. There is no "One Size Fits All" solution to plant problems
- Each situation is to some extent unique
- Adaptive strategies of plants require adaptive management
- Techniques can be applied in a wide range of levels and combinations

5. It is unusual to successfully manage all plants in a lake with one technique
- Variation in lake and plant features usually calls for multiple techniques
- Initial control and follow-up maintenance often require different approaches

6. Prevention is far less expensive than restoration
- Prevention costs are mainly associated with monitoring, regulation and small scale action
- Restoration costs typically involve expansive and repeated control efforts
- If restoration is achieved, additional prevention costs then apply

7. A regional focus is needed to protect the investment made in control

- Re-infestation from nearby lakes can reduce control longevity
- Control on a larger scale can be more efficient and economical
- Prevention measures are more effective on a regional scale

Table 3. Management Options for Control of Algae. (Adapted from Wagner 2001).

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
WATERSHED CONTROLS			
1) Management for nutrient input reduction	- Includes wide range of watershed and lake edge activities intended to eliminate nutrient sources or reduce delivery to lake - Essential component of algal control strategy where internal recycling is not the dominant nutrient source, and desired even where internal recycling is important	- Acts against the original source of algal nutrition - Creates sustainable limitation on algal growth - May control delivery of other unwanted pollutants to lake - Facilitates ecosystem management approach which considers more than just algal control	- May involve considerable lag time before improvement observed - May not be sufficient to achieve goals without some form of in-lake management - Reduction of overall system fertility may impact fisheries - May cause shift in nutrient ratios which favor less desirable algae
1a) Point source controls	- More stringent discharge requirements - May involve diversion - May involve technological or operational adjustments - May involve pollution prevention plans	- Often provides major input reduction - Highly efficient approach in most cases - Success easily monitored	- May be very expensive in terms of capital and operational costs - May transfer problems to another watershed - Variability in results may be high in some cases
1b) Non-point source controls	- Reduction of sources of nutrients - May involve elimination of land uses or activities that release nutrients - May involve alternative product use, as with no phosphate fertilizer	- Removes source - Limited or no ongoing costs	- May require purchase of land or activity - May be viewed as limitation of "quality of life" - Usually requires education and gradual implementation

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
1c) Non-point source pollutant trapping	- Capture of pollutants between source and lake - May involve drainage system alteration - Often involves wetland treatments (detention/infiltration) - May involve stormwater collection and treatment as with point sources	- Minimizes interference with land uses and activities - Allows diffuse and phased implementation throughout watershed - Highly flexible approach - Tends to address wide range of pollutant loads	- Does not address actual sources - May be expensive on necessary scale - May require substantial maintenance
IN-LAKE PHYSICAL CONTROLS	-	-	-
2) Circulation and destratification	- Use of water or air to keep water in motion - Intended to prevent or break stratification - Generally driven by mechanical or pneumatic force	- Reduces surface build-up of algal scums - May disrupt growth of blue-green algae - Counteraction of anoxia improves habitat for fish/invertebrates - May reduce internal loading of phosphorus	- May spread localized impacts - May lower oxygen levels in shallow water - May promote downstream impacts
3) Dilution and flushing	- Addition of water of better quality can dilute nutrients - Addition of water of similar or poorer quality flushes system to minimize algal build-up - May have continuous or periodic additions	- Dilution reduces nutrient concentrations without altering load - Flushing minimizes detention; response to pollutants may be reduced	- Diverts water from other uses - Flushing may wash desirable zooplankton from lake - Use of poorer quality water increases loads - Possible downstream impacts
4) Drawdown	- Lowering of water over autumn period allows oxidation, desiccation and compaction of sediments - Duration of exposure and degree of dewatering of exposed areas are important - Algae are affected mainly by reduction in available nutrients.	- May reduce available nutrients or nutrient ratios, affecting algal biomass and composition - Opportunity for shoreline clean-up/structure repair - Flood control utility - May provide rooted plant control as well	- Possible impacts on non-target resources - Possible impairment of water supply - Alteration of downstream flows and winter water level - May result in greater nutrient availability if flushing inadequate

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
5) Dredging	- Sediment is physically removed by wet or dry excavation, with deposition in a containment area for dewatering - Dredging can be applied on a limited basis, but is most often a major restructuring of a severely impacted system - Nutrient reserves are removed and algal growth can be limited by nutrient availability	- Can control algae if internal recycling is main nutrient source - Increases water depth - Can reduce pollutant reserves - Can reduce sediment oxygen demand - Can improve spawning habitat for many fish species - Allows complete renovation of aquatic ecosystem	- Temporarily removes benthic invertebrates - May create turbidity - May eliminate fish community (complete dry dredging only) - Possible impacts from containment area discharge - Possible impacts from dredged material disposal - Interference with recreation or other uses during dredging
5a) “Dry” excavation	- Lake drained or lowered to maximum extent practical - Target material dried to maximum extent possible - Conventional excavation equipment used to remove sediments	- Tends to facilitate a very thorough effort - May allow drying of sediments prior to removal - Allows use of less specialized equipment	- Rarely truly a dry operation; tends to be messy - Eliminates most aquatic biota unless a portion left undrained - Eliminates lake use during dredging
5b) “Wet” excavation	- Lake level may be lowered, but sediments not substantially exposed - Draglines, bucket dredges, or long-reach backhoes used to remove sediment	- Requires least preparation time or effort, tends to be least cost dredging approach - May allow use of easily acquired equipment - May preserve aquatic biota	- Usually creates extreme turbidity - Normally requires intermediate containment area to dry sediments prior to hauling - May disrupt ecological function - Disrupts many uses
5c) Hydraulic removal	- Lake level not reduced - Suction or cutterhead dredges create slurry which is hydraulically pumped to containment area - Slurry is dewatered; sediment retained, water discharged	- Creates minimal turbidity and impact on biota - Can allow some lake uses during dredging - Allows removal with limited access or shoreline disturbance	- Often leaves some sediment behind - Cannot handle coarse or debris-laden materials - Requires sophisticated and more expensive containment area

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
6) Light-limiting dyes and surface covers	- Creates light limitation	- Creates light limit on algal growth without high turbidity or great depth - May achieve some control of rooted plants as well	- May cause thermal stratification in shallow ponds - May facilitate anoxia at sediment interface with water
6.a) Dyes	- Water-soluble dye is mixed with lake water, thereby limiting light penetration and inhibiting algal growth - Dyes remain in solution until washed out of system.	- Produces appealing color - Creates illusion of greater depth	- May not control surface bloom-forming species - May not control growth of shallow water algal mats - Alters thermal regime
6.b) Surface covers	- Opaque sheet material applied to water surface	- Minimizes atmospheric and wildlife pollutant inputs	- Minimizes atmospheric gas exchange - Limits recreational use
7) Mechanical removal	- Filtering of pumped water for water supply purposes - Collection of floating scums or mats with booms, nets, or other devices - Continuous or multiple applications per year usually needed	- Algae and associated nutrients can be removed from system - Surface collection can be applied as needed - May remove floating debris - Collected algae dry to minimal volume	- Filtration requires high backwash and sludge handling capability for use with high algal densities - Labor and/or capital intensive - Variable collection efficiency - Possible impacts on non-target aquatic life
8) Selective withdrawal	- Discharge of bottom water which may contain (or be susceptible to) low oxygen and higher nutrient levels - May be pumped or utilize passive head differential	- Removes targeted water from lake efficiently - Complements other techniques such as drawdown or aeration - May prevent anoxia and phosphorus build up in bottom water - May remove initial phase of algal blooms which start in deep water - May create coldwater conditions downstream	- Possible downstream impacts of poor water quality - May eliminate colder thermal layer that supports certain fish - May promote mixing of remaining poor quality bottom water with surface waters - May cause unintended drawdown if inflows do not match withdrawal

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
9) Sonication	- Sound waves disrupt algal cells	- Supposedly affects only algae (new technique) - Applicable in localized areas	- Uncertain effects on non-target organisms - May release cellular toxins or other undesirable contents into water column
IN-LAKE CHEMICAL CONTROLS	-	-	-
10) Hypolimnetic aeration or oxygenation	- Addition of air or oxygen at varying depth provides oxic conditions - May maintain or break stratification - Can also withdraw water, oxygenate, then replace	- Oxic conditions promote binding/sedimentation of phosphorus - Counteraction of anoxia improves habitat for fish/invertebrates - Build-up of dissolved iron, manganese, sulfide, ammonia and phosphorus reduced	- May accidentally disrupt thermal layers important to fish community - Theoretically promotes supersaturation with gases harmful to fish - Biota may become dependent on continued aeration
11) Algaecides	- Liquid or pelletized algaecides applied to target area - Algae killed by direct toxicity or metabolic interference - Typically requires application at least once/yr, often more frequently	- Rapid elimination of algae from water column, normally with increased water clarity - May result in net movement of nutrients to bottom of lake	- Possible toxicity to non-target species - Restrictions on water use for varying time after treatment - Increased oxygen demand and possible toxicity - Possible recycling of nutrients
11a) Forms of copper	- Cellular toxicant, suggested disruption of photosynthesis, nitrogen metabolism, and membrane transport - Applied as wide variety of liquid or granular formulations, often in conjunction with chelators, polymers, surfactants or herbicides	- Effective and rapid control of many algae species - Approved for use in most water supplies	- Possible toxicity to aquatic fauna - Ineffective at colder temperatures - Accumulation of copper in system - Resistance by certain green and blue-green nuisance species - Rupturing of cells releases nutrients and toxins

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
11b) Synthetic organic herbicides	- Absorbed or membrane-active chemicals which disrupt metabolism - Causes structural deterioration	- Used where copper is ineffective - Limited toxicity to fish at recommended dosages - Rapid action	- Non-selective in treated area - Possible toxicity to aquatic fauna (varying degrees by dose and formulation) - Time delays on water use
11c) Oxidants	- Disrupts most cellular functions, tends to attack membranes - Applied most often as a liquid.	- Potential selectivity against blue-greens - Moderate control of thick algal mats, used where copper alone is ineffective - Rapid action	- Older formulations tended to have high toxicity to some aquatic fauna - New formulations not well tested in the field yet
12) Phosphorus inactivation	- Typically salts of aluminum, iron or calcium are added to the lake, as liquid or powder - Phosphorus in the treated water column is complexed and settled to the bottom of the lake - Phosphorus in upper sediment layer is complexed, reducing release from sediment - Permanence of binding varies by binder in relation to redox potential and pH	- Can provide rapid, major decrease in phosphorus concentration in water column - Can minimize release of phosphorus from sediment - May remove other nutrients and contaminants as well as phosphorus - Flexible with regard to depth of application and speed of improvement	- Possible toxicity to fish and invertebrates, mainly by aluminum at low or high pH - Possible release of phosphorus under anoxia (with Fe) or extreme pH (with Ca) - May cause fluctuations in water chemistry, especially pH, during treatment - Possible resuspension of floc in shallow areas - Adds to bottom sediment, but typically an insignificant amount
13) Sediment oxidation	- Addition of oxidants, binders and pH adjusters to oxidize sediment - Binding of phosphorus is enhanced - Denitrification is stimulated	- Can reduce phosphorus supply to algae - Can alter N:P ratios in water column - May decrease sediment oxygen demand	- Possible impacts on benthic biota - Longevity of effects not well known - Possible source of nitrogen for blue-green algae

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
14) Settling agents	- Closely aligned with phosphorus inactivation, but can be used to reduce algae directly too - Lime, alum or polymers applied, usually as a liquid or slurry - Creates a floc with algae and other suspended particles - Floc settles to bottom of lake - Re-application typically necessary at least once/yr	- Removes algae and increases water clarity without lysing most cells - Reduces nutrient recycling if floc sufficient - Removes non-algal particles as well as algae - May reduce dissolved phosphorus levels at the same time	- Possible impacts on aquatic fauna - Possible fluctuations in water chemistry during treatment - Resuspension of floc possible in shallow, well-mixed waters - Promotes increased sediment accumulation
15) Selective nutrient addition	- Ratio of nutrients changed by additions of selected nutrients - Addition of non-limiting nutrients can change composition of algal community - Processes such as settling and grazing can then reduce algal biomass (productivity can actually increase, but standing crop can decline)	- Can reduce algal levels where control of limiting nutrient not feasible - Can promote non-nuisance forms of algae - Can improve productivity of system without increased standing crop of algae	- May result in greater algal abundance through uncertain biological response - May require frequent application to maintain desired ratios - Possible downstream effects
IN-LAKE BIOLOGICAL CONTROLS	-	-	-
16) Enhanced grazing	- Manipulation of biological components of system to achieve grazing control over algae - Typically involves alteration of fish community to promote growth of large herbivorous zooplankton, or stocking with phytophagous fish	- May increase water clarity by changes in algal biomass or cell size distribution without reduction of nutrient levels - Can convert unwanted biomass into desirable form (fish) - Harnesses natural processes to produce desired conditions	- May involve introduction of exotic species - Effects may not be controllable or lasting - May foster shifts in algal composition to even less desirable forms

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
16.a) Herbivorous fish (not permitted in MA)	- Stocking of fish that eat algae	- Converts algae directly into potentially harvestable fish - Grazing pressure can be adjusted through stocking rate	- Typically requires introduction of non-native species - Difficult to control over long term - Smaller algal forms may be benefited and bloom
16.b) Herbivorous zooplankton	- Reduction in planktivorous fish to promote grazing pressure by zooplankton - May involve stocking piscivores or removing planktivores - May also involve stocking zooplankton or establishing refugia	- Converts algae indirectly into harvestable fish - Zooplankton response to increasing algae can be rapid - May be accomplished without introduction of non-native species - Generally compatible with most fishery management goals	- Highly variable response expected; temporal and spatial variability may be high - Requires careful monitoring and management action on 1-5 yr basis - Larger or toxic algal forms may be benefited and bloom
17) Bottom-feeding fish removal	- Removes fish that browse among bottom deposits, releasing nutrients to the water column by physical agitation and excretion	- Reduces turbidity and nutrient additions from this source - May restructure fish community in more desirable manner	- Targeted fish species are difficult to eradicate or control - Reduction in fish populations valued by some lake users (human/non-human)
18) Pathogens	- Addition of inoculum to initiate attack on algal cells - May involve fungi, bacteria or viruses	- May create lakewide "epidemic" and reduction of algal biomass - May provide sustained control through cycles - Can be highly specific to algal group or genera	- Largely experimental approach at this time - May promote resistant nuisance forms - May cause high oxygen demand or release of toxins by lysed algal cells - Effects on non-target organisms uncertain
19) Competition and allelopathy	- Plants may tie up sufficient nutrients to limit algal growth - Plants may create a light limitation on algal growth - Chemical inhibition of algae may occur through substances released by other organisms	- Harnesses power of natural biological interactions - May provide responsive and prolonged control	- Some algal forms appear resistant - Use of plants may lead to problems with vascular plants - Use of plant material may cause depression of oxygen levels

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
19a) Plantings for nutrient control	- Plant growths of sufficient density may limit algal access to nutrients - Plants can exude allelopathic substances which inhibit algal growth - Portable plant "pods" , floating islands, or other structures can be installed	- Productivity and associated habitat value can remain high without algal blooms - Can be managed to limit interference with recreation and provide habitat - Wetland cells in or adjacent to the lake can minimize nutrient inputs	- Vascular plants may achieve nuisance densities - Vascular plant senescence may release nutrients and cause algal blooms - The switch from algae to vascular plant domination of a lake may cause unexpected or undesirable changes
19b) Plantings for light control	- Plant species with floating leaves can shade out many algal growths at elevated densities	- Vascular plants can be more easily harvested than most algae - Many floating species provide valuable waterfowl food	- At the necessary density, floating plants likely to be a recreational nuisance - Low surface mixing and atmospheric contact promote anoxia
19c) Addition of barley straw	- Input of barely straw can set off a series of chemical reactions which limit algal growth - Release of allelopathic chemicals can kill algae - Release of humic substances may bind phosphorus	- Materials and application are relatively inexpensive - Decline in algal abundance is more gradual than with algaecides, limiting oxygen demand and the release of cell contents	- Success appears linked to uncertain and potentially uncontrollable water chemistry factors - Depression of oxygen levels may result - Water chemistry may be altered in other ways unsuitable for non-target organisms

Table 4. Management Options for Control of Rooted Aquatic Plants. (Adapted from Wagner, 2001).

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
PHYSICAL CONTROLS			
1) Benthic barriers	- Mat of variable composition laid on bottom of target area, preventing growth - Can cover area for as little as several months or permanently - Maintenance improves results - Usually applied around docks, in boating lanes, and in swimming areas	- Highly flexible control - Reduces turbidity from soft bottom sediments - Can cover undesirable substrate - Can improve fish habitat by creating edge effects	- May cause anoxia at sediment-water interface - May limit benthic invertebrates - Non-selective interference with plants in target area - May inhibit spawning/feeding by some fish species
1.a) Porous or loose-weave synthetic materials	- Laid on bottom and usually anchored by weights or stakes - Removed and cleaned or flipped and repositioned at least once per year for maximum effect	- Allows some escape of gases which may be generated underneath - Panels may be flipped in place or removed for relatively easy cleaning or repositioning	- Allows some plant growth through pores - Gas may still build up underneath in some cases, lifting barrier from bottom
1.b) Non-porous or sheet synthetic materials	- Laid on bottom and anchored by many stakes, anchors or weights, or by layer of sand - Not typically removed, but may be swept or “blown” clean periodically	- Prevents all plant growth until buried by sediment - Minimizes interaction of sediment and water column	- Gas build up may cause barrier to float upwards - Strong anchoring makes removal difficult and can hinder maintenance
1.c) Improving sediment composition	- Sediments may be added on top of existing sediments or plants. - Use of sand or clay can limit plant growths and alter sediment-water interactions. - Sediments can be applied from the surface or suction dredged from below muck layer (reverse layering technique)	- Plant biomass can be buried - Seed banks can be buried deeper - Sediment can be made less hospitable to plant growths - Nutrient release from sediments may be reduced - Surface sediment can be made more appealing to human users - Reverse layering requires no addition or removal of sediment	- Lake depth may decline - Sediments may sink into or mix with underlying muck - Permitting for added sediment difficult - Addition of sediment may cause initial turbidity increase - New sediment may contain nutrients or other contaminants - Generally too expensive for large scale application

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
2) Dredging	- Sediment is physically removed by wet or dry excavation, with deposition in a containment area for dewatering/disposal - Dredging can be applied on a limited basis, but is most often a major restructuring of a severely impacted system - Plants and seed beds are removed and re-growth can be limited by light and/or substrate limitation	- Plant removal with some flexibility - Increases water depth - Can reduce pollutant reserves - Can reduce sediment oxygen demand - Can improve spawning habitat for many fish species - Allows complete renovation of aquatic ecosystem - May allow for growth of desirable species.	- Temporarily removes benthic invertebrates - May create turbidity - May eliminate fish community (complete dry dredging only) - Possible impacts from containment area discharge - Possible impacts from dredged material disposal - Interference with recreation or other uses during dredging - Usually very expensive
2.a) "Dry" excavation	- Lake drained or lowered to maximum extent practical - Target material dried to maximum extent possible - Conventional excavation equipment used to remove sediments	- Tends to facilitate a very thorough effort - May allow drying of sediments prior to removal - Allows use of less specialized equipment	- Eliminates most aquatic biota unless a portion left undrained - Eliminates lake use during dredging
2.b) "Wet" excavation	- Lake level may be lowered, but sediments not substantially dewatered - Draglines, bucket dredges, or long-reach backhoes used to remove sediment	- Requires least preparation time or effort, tends to be least cost dredging approach - May allow use of easily acquired equipment - May preserve most aquatic biota	- Usually creates extreme turbidity - Tends to result in sediment deposition in surrounding area - Normally requires intermediate containment area to dry sediments prior to hauling - May cause severe disruption of ecological function - Impairs most lake uses during dredging

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
2.c) Hydraulic (or pneumatic) removal	- Lake level not reduced - Suction or cutterhead dredges create slurry which is hydraulically pumped to containment area - Slurry is dewatered; sediment retained, water discharged	- Creates minimal turbidity and limits impact on biota - Can allow some lake uses during dredging - Allows removal with limited access or shoreline disturbance	- Often leaves some sediment behind - Cannot handle extremely coarse or debris-laden materials - Requires advanced and more expensive containment area - Requires overflow discharge from containment area
3) Dyes and surface covers	- Water-soluble dye is mixed with lake water, thereby limiting light penetration and inhibiting plant growth - Dyes remain in solution until washed out of system. - Opaque sheet material applied to water surface	- Light limit on plant growth without high turbidity or great depth - May achieve some control of algae as well - May achieve some selectivity for species tolerant of low light	- May not control peripheral or shallow water rooted plants - May cause thermal stratification in shallow ponds - May facilitate anoxia at sediment interface with water - Covers inhibit gas exchange with atmosphere and restrict recreation - Cannot be used in water bodies with an active outlet
4) Mechanical removal (“harvesting”)	- Plants reduced by mechanical means, possibly with disturbance of soils - Collected plants may be placed on shore for composting or other disposal - Wide range of techniques employed, from manual to highly mechanized - Application once or twice per year usually needed	- Highly flexible control - May remove other debris - Can balance habitat and recreational needs	- Possible impacts on aquatic fauna - Non-selective removal of plants in treated area - Possible spread of undesirable species by fragmentation - Possible generation of turbidity
4.a) Hand pulling	- Plants uprooted by hand (“weeding”) and preferably removed	- Highly selective technique	- Labor intensive - Difficult to perform in dense stands - Can cause fragmentation

4.b) Cutting (without collection)	- Plants cut in place above roots without being harvested	- Generally efficient and less expensive than complete harvesting	- Leaves root systems and part of plant for possible re-growth - Leaves cut vegetation to decay or to re-root - Not selective within applied area
4.c) Harvesting (with collection)	- Plants cut at depth of 2-10 ft and collected for removal from lake	- Allows plant removal on greater scale	- Limited depth of operation - Usually leaves fragments which may re-root and spread infestation - May impact lake fauna - Limited selectivity within applied area - More expensive than cutting
4.d) Rototilling	- Plants, root systems, and surrounding sediment disturbed with mechanical blades	- Can thoroughly disrupt entire plant	- Usually leaves fragments which may re-root and spread infestation - May impact lake fauna - Not selective within applied area - Creates substantial turbidity - More expensive than harvesting
4.e) Hydroraking	- Plants, root systems and surrounding sediment and debris disturbed with mechanical rake, part of material usually collected and removed from lake	- Can thoroughly disrupt entire plant - Also allows removal of stumps or other obstructions	- Usually leaves fragments which may re-root and spread infestation - May impact lake fauna - Not selective within applied area - Creates substantial turbidity - More expensive than harvesting
5) Water level control	- Lowering or raising the water level to create an inhospitable environment for some or all aquatic plants - Disrupts plant life cycle by dessication, freezing, or light limitation	- Requires only outlet control to affect large area - Provides widespread control in increments of water depth - Complements certain other techniques (dredging, flushing)	- Potential issues with water supply - Potential issues with flooding - Potential impacts to non-target flora and fauna

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
5.a) Drawdown	- Lowering of water over winter period allows desiccation, freezing, and physical disruption of plants, roots and seed beds - Timing and duration of exposure and degree of dewatering are critical aspects - Variable species tolerance to drawdown; emergent species and seed-bearers are less affected - Most effective on annual to once/3 yr. basis	- Control with some flexibility - Opportunity for shoreline clean-up/structure repair - Flood control utility - Impacts vegetative propagation species with limited impact to seed producing populations	- Possible impacts on contiguous emergent wetlands - Possible effects on overwintering reptiles and amphibians - Possible impairment of well production - Reduction in potential water supply and fire fighting capacity - Alteration of downstream flows - Possible overwinter water level variation - Possible shoreline erosion and slumping - May result in greater nutrient availability for algae
5.b) Flooding	- Higher water level in the spring can inhibit seed germination and plant growth - Higher flows which are normally associated with elevated water levels can flush seed and plant fragments from system	- Where water is available, this can be an inexpensive technique - Plant growth need not be eliminated, merely retarded or delayed - Timing of water level control can selectively favor certain desirable species	- Water for raising the level may not be available - Potential peripheral flooding - Possible downstream impacts - Many species may not be affected, and some may be benefitted - Algal nuisances may increase where nutrients are available
CHEMICAL CONTROLS	-	-	-
6) Herbicides	- Liquid or pelletized herbicides applied to target area or to plants directly - Contact or systemic poisons kill plants or limit growth - Typically requires application every 1-5 yrs	- Wide range of control is possible - May be able to selectively eliminate species - May achieve some algae control as well - May allow for more desirable plant growth	- Possible toxicity to non-target species - Possible downstream impacts - Restrictions of water use for varying time after treatment - Increased oxygen demand from decaying vegetation - Possible recycling of nutrients to allow other growths

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
6.a) Forms of copper	- Contact herbicide - Cellular toxicant, suspected membrane transport disruption - Applied as wide variety of liquid or granular formulations, often in conjunction with polymers or other herbicides	- Moderately effective control of some submersed plant species - More often an algal control agent	- Potentially toxic to aquatic fauna as a function of concentration, formulation, and ambient water chemistry - Ineffective at colder temperatures - Copper ion persistent; accumulates in sediments or moves downstream
6.b) Forms of endothall (7-oxabicyclo [2.2.1] heptane-2,3-dicarboxylic acid)	- Contact herbicide with limited translocation potential - Membrane-active chemical which inhibits protein synthesis - Causes structural deterioration - Applied as liquid or granules	- Moderate control of some emersed plant species, moderately to highly effective control of floating and submersed species - Limited toxicity to fish at typical MA dosages - Rapid action	- Non-selective in treated area - Potentially toxic to aquatic fauna (varying degrees by formulation) - Time delays on use for water supply, agriculture and recreation
6.c) Forms of diquat (6,7-dihydropyrido [1,2-2',1'-c] pyrazinediium dibromide)	- Contact herbicide - Absorbed by foliage but not roots - Strong oxidant; disrupts most cellular functions - Applied as a liquid, sometimes in conjunction with copper	- Moderate control of some emersed plant species, moderately to highly effective control of floating or submersed species - Limited toxicity to fish at recommended dosages, low toxicity at typical MA doses - Rapid action	- Non-selective in treated area - Potentially toxic to zooplankton at high application rates - Inactivated by suspended particles; ineffective in muddy waters
6.d) Forms of glyphosate (N-[phosphonomethyl glycine)	- Contact herbicide - Absorbed through foliage, disrupts enzyme formation and function in uncertain manner - Applied as liquid spray	- Moderately to highly effective control of emergent and floating plant species - Can be used selectively, based on application to individual plants - Rapid action - Low toxicity to aquatic fauna at recommended dosages - No time delays for use of treated water	- Non-selective in treated area - Inactivation by suspended particles; ineffective in muddy waters - Not for use within 0.5 miles of potable surface water intakes

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
6.e) Forms of 2,4-D (2,4-dichlorophenoxyl acetic acid)	- Systemic herbicide - Readily absorbed and translocated throughout plant - Inhibits cell division in new tissue, stimulates growth in older tissue, resulting in gradual cell disruption - Applied as liquid or granules, frequently as part of more complex formulations, preferably during early growth phase of plants	- Moderately to highly effective control of a variety of emergent, floating and submersed plant species - Can achieve some selectivity through application timing and concentration - Fairly fast action	- Potential toxicity to aquatic fauna, depending upon formulation and ambient water chemistry - Time delays for use of treated water for agriculture and recreation - Not for use in potable water supplies
6.f) Forms of fluridone (1-methyl-3-phenyl-5-[-3-{trifluoromethyl} phenyl]-4[IH]-pyridinone)	- Systemic herbicide - Inhibits carotenoid pigment synthesis and impacts photosynthesis - Best applied as liquid or granules during early growth phase of plants	- Can be used selectively, based on concentration - Gradual deterioration of affected plants limits impact on oxygen level (BOD) - Effective against several difficult-to-control species - Low toxicity to aquatic fauna	- Impacts on non-target plant species possible at higher doses - Extremely soluble and mixable; difficult to perform partial lake treatments - Requires extended contact time
6.g Forms of triclopyr (3,5,6-trichloro-2-pyridinyloxyacetic acid)	- Systemic herbicide, registration pending in MA at this time - Readily absorbed by foliage, translocated throughout plant - Disrupts enzyme systems specific to plants - Applied as liquid spray or subsurface injected liquid	- Effectively controls many floating and submersed plant species - Can be used selectively, more effective against dicot plant species, including many nuisance species - Effective against several difficult-to-control species - Low toxicity to aquatic fauna - Fast action	- Impacts on non-target plant species possible at higher doses - Restrictions on use of treated water for supply or recreation not yet certain for MA - Registration not complete in MA at time of table preparation

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
BIOLOGICAL CONTROLS			
7) Biological introductions	- Fish, insects or pathogens which feed on or parasitize plants are added to system to affect control - The most commonly used organism is the grass carp, but the larvae of several insects have been used more recently, and viruses are being tested	- Provides potentially continuing control with one treatment - Harnesses biological interactions to produce desired conditions - May produce potentially useful fish biomass as an end product	- Typically involves introduction of non-native species - Effects may not be controllable - Plant selectivity may not match desired target species - May adversely affect indigenous species
7.a) Herbivorous fish	- Sterile juveniles stocked at density which allows control over multiple years - Growth of individuals offsets losses or may increase herbivorous pressure. Grass carp are illegal in Massachusetts.	- May greatly reduce plant biomass in single season - May provide multiple years of control from single stocking - Sterility intended to prevent population perpetuation and allow later adjustments	- May eliminate all plant biomass, or impact non-target species - Funnels energy into algae - Alters habitat - May escape upstream or downstream - Population control issues
7.b) Herbivorous insects	- Larvae or adults stocked at density intended to allow control with limited growth - Intended to selectively control target species - Milfoil weevil is best known, but still experimental	- Involves species native to region, or even targeted lake - Expected to have no negative effect on non-target species - May facilitate longer term control with limited management	- Population ecology suggests incomplete control likely - Oscillating cycle of control and re-growth - Predation by fish may complicate control - Other lake management actions may interfere with success
7.c) Fungal/bacterial/viral pathogens	- Inoculum used to seed lake or target plant patch - Growth of pathogen population expected to achieve control over target species	- May be highly species specific - May provide substantial control after minimal inoculation effort	- Effectiveness and longevity of control not well known - Infection ecology suggests incomplete control likely
7.d) Selective plantings	- Establishment of plant assemblage resistant to undesirable species - Plants introduced as seeds, cuttings or whole plants	- Can restore native assemblage - Can encourage assemblage most suitable to lake uses - Supplements targeted species removal effort	- Largely experimental - Nuisance species may eventually return assemblage - Introduced species may become nuisances